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Additional Results on the
Statistical Analysis of a Linear Vehicle
Using Measured Ground Power Spectral Density

By

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November 1963

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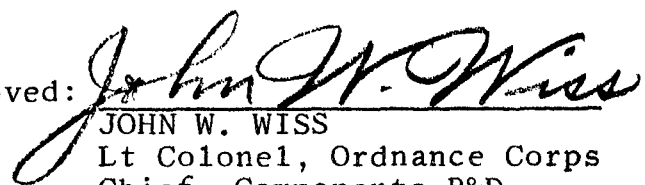
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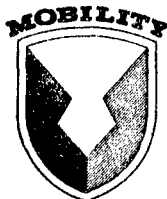
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An extension is presented of previous results of the authors relating the parameters of an idealized two-dimensional linear vehicle to stable ground roughness as described by power spectral densities. Optimal vehicle parameters are obtained relative to a ride roughness criterion for ground contours described by power spectral densities estimated from real ground survey data. It is found that the ride is not sensitive to changes in the wheel base length parameter when this is over 14 feet. However, the ride is found to be sensitive to damping and speed in this wheel base length range.

OBJECT

Determine influence of wheel base length, suspension system damping, and vehicle speed on ride roughness of an idealized two-dimensional linear vehicle with stable ground roughness described in terms of simplified p. s. d. estimated from survey data.

RESULTS

For the class of vehicle, ride roughness criterion, and p. s. d. describing ground roughness considered, ride is not sensitive to changes in the wheel base length parameter when this is over 14 ft. It is sensitive to speed and damping, when the base length is in this range.

CONCLUSIONS

For idealized vehicles (linear) of reasonable size, wheel base length is not as significant a parameter influencing ride roughness as are damping and speed.

ACKNOWLEDGEMENTS

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INTRODUCTION

One aspect of the task of increasing vehicle speeds under off-road conditions is the study of the significance of various vehicle parameters on the roughness of the ride of the vehicle; and, hence, on its maximum speed.

In previous studies conducted by the Midwest Applied Science Corp. on how vehicle parameters influence ride, hypothetical and dimensionless power spectral densities (roughness measures of profile height by frequency bands) were employed to specify ground roughness. These studies indicated that for idealized two-dimensional linear vehicles, wheel base length, among other factors, was a significant parameter when ride roughness is assumed to be specified in terms of vertical acceleration p. s. d.

OBJECT

Information is gradually accumulating on characterizing stable ground roughness and those characteristics of vibration which influence humans adversely. As input information and output tolerance limits increase, it becomes important to relate these to vehicle parameters. The object of this study is to determine influence of wheel base length, suspension system damping, and vehicle speed on ride roughness of an idealized two-dimensional linear vehicle with stable ground roughness described in terms of simplified p.s.d. estimated from survey data. Knowledge of these relations may, in turn, modify our approach to ground roughness measurements as well as to studies on humans subject to vibration.

RESULTS

Graphs are presented which indicate the influence of wheel base length, damping, and speed on the variance of the vertical acceleration (ride roughness measure) at two points on the vehicle frame. The power spectral density used to specify ground roughness is the envelope of the p. s. d. estimates obtained from survey data taken at Aberdeen and Knox. At the frame center of gravity and also at a point on the frame forward of the front wheel, acceleration variance is insensitive to the wheel base length parameter as long as this parameter has a value above 14 ft. At the frame c.g., the ride is worst when the wheel base length is approximately 8 feet.

Damping is a significant parameter in determining the roughness of a ride.

Increasing (decreasing) speed produces a rougher (smoother) ride at all practical values of wheel base length and for all values of damping. The steep slope of the p. s. d. curve in the interval from $\lambda = 0$ to $\lambda = .065$ (λ is frequency in cycles per ft.) appears to account for the substantial nature of the change in ride roughness with fairly small changes in vehicle speed.

The portion of the p. s. d. curve above $\lambda = .065$ has only a very small influence on ride roughness. This suggests that if future results on ride roughness show the same lack of sensitivity to values in the portion of the p. s. d. curve above $\lambda = 0.065$ survey, data may be taken at spacings greater than 2 feet.

RECOMMENDATIONS

Continue the investigations for different vehicle configurations and for those criteria of ride roughness which develop from the M.A.S.C. program.

Section I: Review of Previous Work

It will be recalled that all previous statistical studies of idealized two-dimensional linear vehicle response conducted by M.A.S.C. have employed hypothetical and dimensionless p.s.d.'s to characterize the roughness of the ground. Since that time, estimated p.s.d.'s of ground roughness have been obtained from survey data. It now becomes profitable to re-examine some aspects of the vehicle response using estimated rather than hypothetical p.s.d.'s, since the former differ from the latter in more than just dimension.

The main conclusions of this Report apply only to one idealized linear vehicle (with specific springs, masses, geometry, base speed (10 mph), and wheels always in contact with the ground) using vertical motion acceleration variance to measure the roughness of the ride. Briefly, the conclusions are as follows:

- a. In the wheel base length range over 14 ft., base length is not significant in changing "ride" roughness.
- b. Change in vehicle speed from 8.33 mph to 12.5 mph produces substantial increase in ride roughness, indicating for the vehicle considered, the importance of speed, and, thus, the shape of the ground p.s.d. curve in the wave length range over 16 ft.
- c. Damping is a significant parameter in controlling the roughness of the ride.

The detailed analysis and discussion of results obtained follow.

Section II: Linear Vehicle Model and Equations of Motion

The linear vehicle model considered in this section is shown in Figure 1.

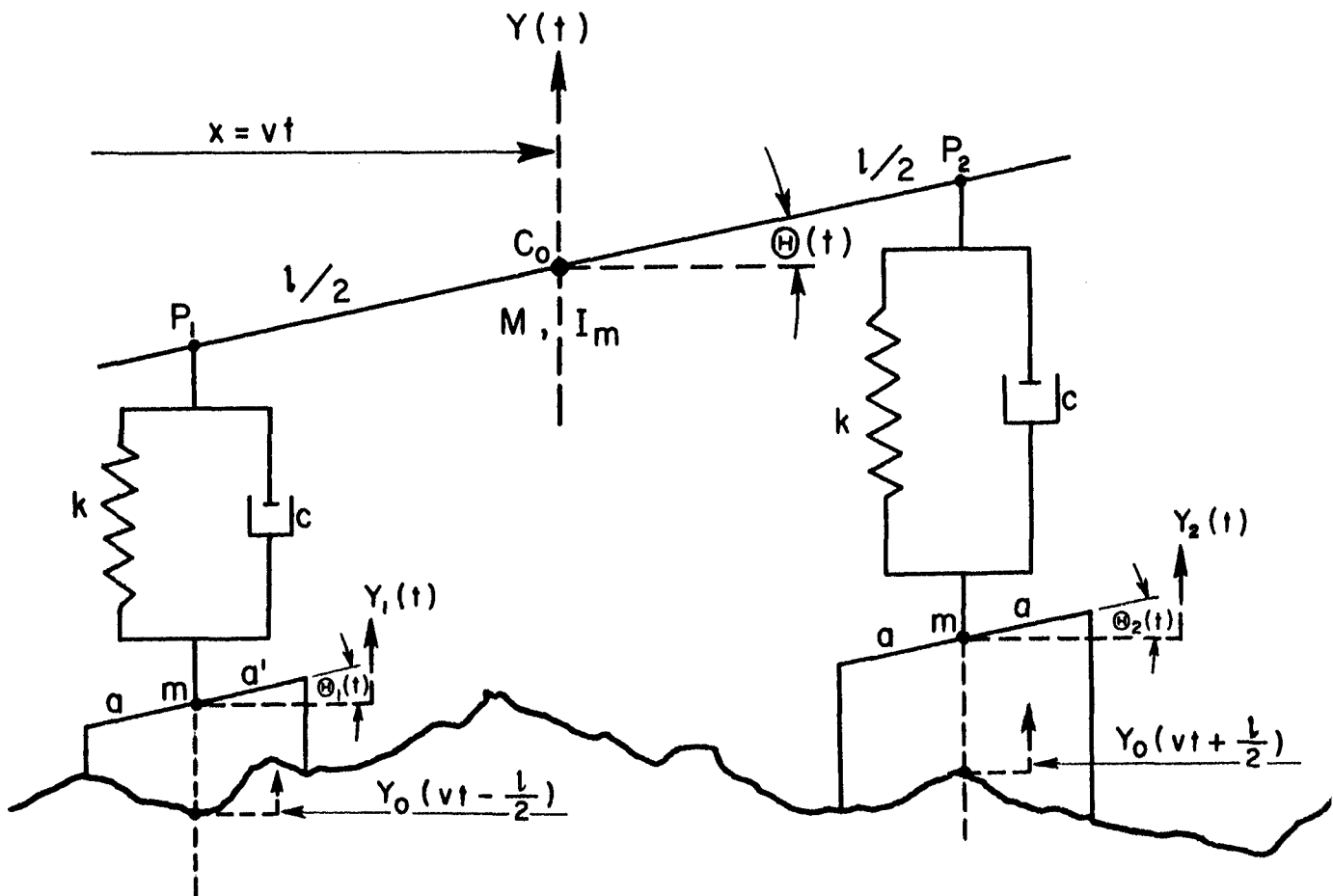


Figure 1.

Schematic Sketch of
Two-dimensional Linear Vehicle

Section III: Analysis

For the purposes of this Report, it suffices to consider a symmetric two-dimensional vehicle. The center of mass C_0 of the vehicle frame $P_1C_0P_2$ is assumed to move with a constant horizontal speed v ; the vertical displacement of C_0 and angular displacement of $P_1C_0P_2$ are $Y(t)$ and $\Theta(t)$, respectively; the mass of the frame is M and the moment of inertia of the frame about C_0 is I_m . The rear and front suspension elements connect to the frame at P_1 and P_2 , as shown in Figure 1; they are $\ell/2$ from C_0 ; the spring elements have modulus k and the damping (linear viscous) elements have modulus c . The wheels have been idealized in a number of ways; their c.g.'s are denoted by Q_1 and Q_2 . We consider their masses m but neglect moments of inertia. The vertical displacements of Q_1 and Q_2 are $Y_1(t)$ and $Y_2(t)$, respectively. There is no driving torque present. The tires are replaced by linear springs and linear viscous dampers distributed over massless bars of length $2a$ which are free to rotate about their centers Q_1 and Q_2 . The angular displacements of the bars are $\Theta_1(t)$ and $\Theta_2(t)$, respectively. The distributed springs and dampers, arranged in parallel, have densities per unit length denoted by $\kappa(\xi)$ and $\lambda(\xi)$, respectively, where ξ is measured from the bar centers.

In summary, the coordinates are

$$Y(t), \Theta(t), Y_1(t), \Theta_1(t), Y_2(t), \Theta_2(t)$$

and the parameters are

$$M, I_m, \ell, k, c, m, a, \kappa(\xi), \lambda(\xi), v$$

The vehicle frame and wheels are confined to a moving vertical plane; the frame can pitch and oscillate vertically; the tire masses can oscillate vertically on the tire springs and dampers and on the suspension system springs and dampers; the tire springs and dampers cling to the track at all times and are distributed over portions of the track each of length $2a$. Finally, the vertical plane containing the vehicle frame and C_0 move with constant horizontal speed v .

For simplicity, we shall assume

$$\kappa(-\xi) = \kappa(\xi) ; \gamma(-\xi) = \gamma(\xi)$$

The track elevation above some arbitrarily selected datum is denoted by the random function $Y_0(x)$, where x is the horizontal distance measured from some arbitrarily selected origin. Because of the constant horizontal speed of the point C_0 ,

$$x = vt \quad (1)$$

Thus, for example, under the point P_1 (and also Q_1) of the rear wheel center, the track elevation is $Y_0(vt - \frac{\ell}{2})$. We shall have more to say about $Y_0(x)$ in the next section.

Before stating the equations of motion, it is convenient to introduce some useful notational changes. We set

$$\begin{aligned} \frac{1}{\ell} Y(t) &= Y'(t) \\ \frac{1}{\ell} Y_1(t) &= Y'_1(t) \\ \frac{1}{\ell} Y_2(t) &= Y'_2(t), \quad \frac{1}{\ell} Y_0(x) = Y'_0(x) \end{aligned} \quad (2)$$

$$\frac{2k}{M} = \omega_y^2, \quad \frac{2c}{M} = 2\zeta_y \omega_y$$

$$\frac{m}{M} = \delta, \quad I_m = M\rho^2$$

$$\kappa = \frac{\ell}{2\rho}, \quad \nu = \frac{v_0}{v} \quad (2)$$

$$\alpha = \frac{\ell \omega_y}{v_0}, \quad \frac{c\ell^2}{2I_m} = 2\zeta_y \omega_y \bar{\kappa}^2$$

$$\frac{k\ell^2}{2I_m} = \omega_y^2 \bar{\kappa}^2, \quad K = \int_{-a}^a \kappa(\xi) d\xi$$

$$\kappa'(\xi) = \frac{\kappa(\xi)}{K}, \quad C = \int_{-a}^a \gamma(\xi) d\xi$$

$$\gamma'(\xi) = \frac{\gamma(\xi)}{C}, \quad \frac{C}{c} = \epsilon_1$$

$$\frac{K}{k} = \epsilon_2, \quad r = \frac{\omega}{\omega_y}$$

The equations of motion are easily seen to be

$$\ddot{Y}' + 2\zeta_y \omega_y \dot{Y}' + \omega_y^2 Y' - \zeta_y \omega_y \dot{Y}'_1 - \frac{\omega_y^2}{2} Y'_1 - \zeta_y \omega_y \dot{Y}'_2 - \frac{\omega_y^2}{2} Y'_2 = 0,$$

$$\ddot{\Theta} + 2\zeta_y \omega_y \bar{\kappa}^2 \dot{\Theta} + \omega_y^2 \bar{\kappa}^2 \Theta + 2\zeta_y \omega_y \bar{\kappa}^2 Y'_1 - \omega_y^2 \bar{\kappa}^2 Y'_1 - 2\zeta_y \omega_y \bar{\kappa}^2 \dot{Y}'_2$$

$$- \omega_y^2 \bar{\kappa}^2 Y'_2 = 0, \quad (3)$$

$$- 2\zeta_y \omega_y \dot{Y}' - \omega_y^2 Y' + \zeta_y \omega_y \dot{\Theta} - \frac{\omega_y^2}{2} \Theta + 2\delta \ddot{Y}'_1 + 2\zeta_y \omega_y (1 + \epsilon_1)$$

$$+ \omega_y^2 (1 + \epsilon_2) Y'_1 = \int_{-a}^a \{\omega_y^2 \epsilon_2 \kappa'(\xi) Y'_0(vt - \frac{\ell}{2} + \xi)$$

$$\begin{aligned}
 & + 2 \zeta_y \omega_y \epsilon_1 \gamma'(\xi) \dot{Y}_0' \left(vt - \frac{\ell}{2} + \xi \right) \} d\xi, \quad (3) \text{ contd.} \\
 & - 2 \zeta_y \omega_y (1 + \epsilon_1) \dot{Y}_2' + \omega_y^2 (1 + \epsilon_2) Y_2' \\
 & = \int_{-a}^a \left\{ \omega_y^2 \epsilon_2 \kappa'(\xi) Y_0' \left(vt + \frac{\ell}{2} + \xi \right) \right. \\
 & \quad \left. + 2 \zeta_y \omega_y \epsilon_1 \gamma'(\xi) \dot{Y}_0' \left(vt + \frac{\ell}{2} + \xi \right) \right\} d\xi
 \end{aligned}$$

The first equation refers to the vertical motion of C_0 ; the second describes the pitch of $P_1 C_0 P_2$; the third and fourth describe the vertical motion of Q_1 and Q_2 , respectively.

As would be expected, the track makes its presence felt only through the third and fourth of (3). The coordinates $\theta_1(t)$ and $\theta_2(t)$ have dropped out because of our assumption that

$$\int_{-a}^a \xi \kappa'(\xi) d\xi = 0, \quad \int_{-a}^a \xi \gamma'(\xi) d\xi = 0$$

i. e., because we have assumed $\kappa(\xi)$ and $\gamma(\xi)$ are symmetrical about Q_1 and Q_2 . The equations are coupled together in a fairly complex manner. Except with respect to t and ξ , (3) are in dimensionless form.

Section IV: Ground Profile

We shall not detail our reasons here for regarding $Y_0(x)$ as a second order stationary random process. These reasons are based upon the analysis of elevation surveys of lines and squares under off-road conditions, and are described in detail in our report entitled, "Statistical Studies of Stable Ground Roughness."

We therefore write

$$Y_0(x) = \int_{-\infty}^{\infty} e^{i\lambda x} dZ(\lambda) \quad (5)$$

where λ has the dimensions $1/L$, Z is an orthogonal process with

$$E \{dZ\} = 0$$

$$E \{dZ|^2\} = 1/2 p_{y_0}(\lambda) d\lambda$$

and $p_{y_0}(\lambda)$ is the power spectral density of $Y_0(x)$. Thus, we will assume that the roughness of $Y_0(x)$ is adequately described in terms of the power spectral density (p. s. d.).

The p. s. d. used in subsequent calculations is shown in Figure 2; the abscissa is frequency with units $1/\text{ft.}$, the ordinate the p. s. d. value with units ft.^3 . In the range $\lambda \leq 0.055$, the graph represents the envelope of two power spectral density estimates obtained from line survey data taken at Aberdeen and Ft. Knox. For $\lambda \geq 0.055$, the graph is a straight line (on semi log paper) with variable slope; this line represents fairly well the general trend of the two p. s. d. estimates in this region of low power. Subsequently, we shall see that the actual value of the slope assumed in computation is of little consequence. Thus, the region of significance in our analysis is $\lambda \leq 0.055$.

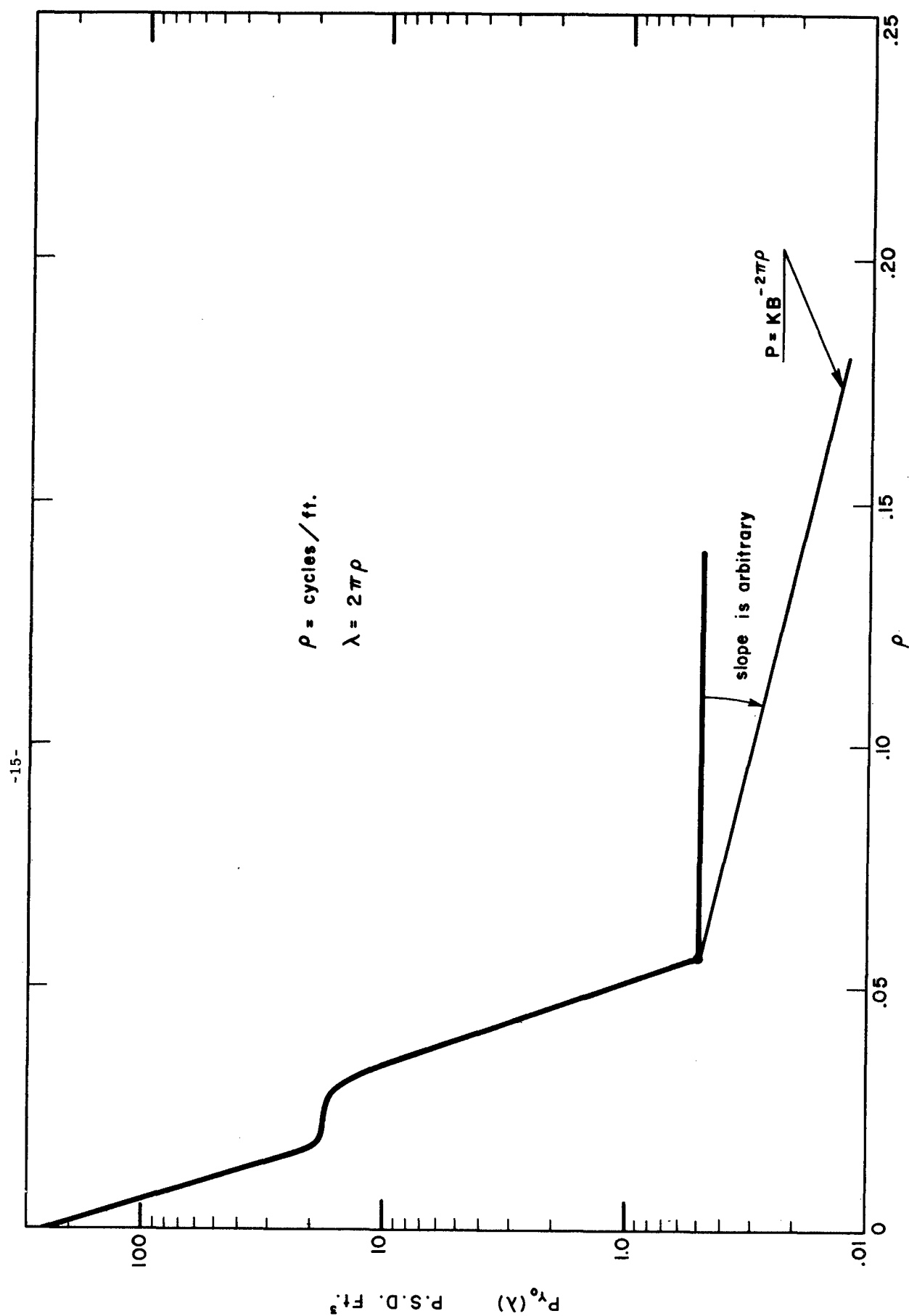


Figure 2.
Power Spectral Density of Off-Road Ground Roughness Used in Calculations

Section V: Response Power Spectral Density

We have assumed the track to have statistical properties which do not change with distance along the track ($Y_0(x)$ is assumed weakly stationary). In virtue of the assumed model and the fact that the horizontal speed of C_0 is a constant v , it follows that $Y(t)$, $\Theta(t)$, $Y_1(t)$, $Y_2(t)$, etc., also have statistical properties which do not change with time, i.e., they possess p.s.d.'s.

We are interested in the p.s.d. of $Y(t)$ and $\Theta(t)$; we therefore assume that

$$\begin{aligned} Y'(t) &= \int_{-\infty}^{\infty} e^{i\omega t} dU'(\omega) \\ \Theta(t) &= \int_{-\infty}^{\infty} e^{i\omega t} dV(\omega) \\ Y_1'(t) &= \int_{-\infty}^{\infty} e^{i\omega t} dW_1'(\omega) \\ Y_2'(t) &= \int_{-\infty}^{\infty} e^{i\omega t} dW_2'(\omega) \end{aligned} \quad (7)$$

The substitution of these into (3) permits us to determine the p.s.d. of

$$Y'(t) + \frac{z}{l} \Theta(t)$$

which is the dimensionless displacement of any point on the frame distance z from C_0 . Since we are primarily interested in the p.s.d. of the ac-

celeration of this point, we shall only write out the p. s. d. of

$$\ddot{Y}(t) + z \ddot{\Theta} ; \quad (8)$$

it is

$$\frac{p \ddot{Y} + z \ddot{\Theta}}{\omega_y^4 \sigma_{y0}^2} = r^2 \frac{\alpha \nu \Lambda}{2} \frac{p'_{Y0} \left(\frac{\alpha \nu r}{l} \right)}{l} \quad (9)$$

where

$$\begin{aligned} \Lambda = & \left[\frac{a^2 + b^2}{c^2 + d^2} (1 + \cos \alpha \nu r) \Pi_1^2 \right. \\ & - \frac{4z}{l} \Pi_1 \frac{(c'd - cd') (a^2 + b^2)}{(c'^2 + d'^2)(c^2 + d^2)} \sin \alpha \nu r \\ & \left. + \frac{4z^2}{l^2} \frac{a^2 + b^2}{c'^2 + d'^2} (1 - \cos \alpha \nu r) \right] \left(\frac{\sin r \alpha \nu \frac{a}{l}}{r \alpha \nu \frac{a}{l}} \right)^2 \end{aligned} \quad (10)$$

$$\sigma_{Y0}^2 = \int_0^\infty p_{Y0}(\lambda) d\lambda$$

(11)

$$p'_{Y0}(\lambda) = \frac{1}{\sigma^2} p_{Y0}(\lambda)$$

$$a = \epsilon_2 - 4\zeta_y^2 \epsilon_1 r^2$$

$$b = 2\zeta_y r (\epsilon_1 + \epsilon_2)$$

$$c = (1-r^2)(1 + \epsilon_2 - 2\delta r^2) - 4\zeta_y^2 (1 + \epsilon_1)r^2 - (1-4\zeta_y^2 r^2)$$

$$d = 2\zeta_y [(1 + \epsilon_1)(1-r^2) + 1 + \epsilon_2 - 2\delta r^2]r - 4\zeta_y r$$

$$c' = (1 - \frac{r^2}{\kappa}) (1 + \epsilon_2 - 2\delta r^2) - 4\zeta_y^2 (1 + \epsilon_1)r^2 - (1 - 4\zeta_y^2 r^2)$$

$$d' = 2\zeta_y [(1 + \epsilon_1)(1 - \frac{r^2}{\kappa}) + 1 + \epsilon_2 - 2\delta r^2]r - 4\zeta_y r$$

$$\omega_y^2 = \frac{2k}{M}, \quad 2\zeta_y \omega_y = \frac{2c}{M}$$

$$\frac{c\ell^2}{2I_m} = 2\zeta_y \omega_y \bar{\kappa}^2, \quad \frac{k\ell^2}{2I_m} \omega_y^2 \bar{\kappa}^2$$

$$I_m = M\rho^2, \quad \bar{\kappa} = \frac{\ell}{2\rho}$$

$$\frac{m}{M} = \delta, \quad \frac{C}{c} = \epsilon_1$$

$$\frac{K}{k} = \epsilon_2, \quad \alpha = \frac{\ell \omega_y}{v_o}$$

$$\nu = \frac{v_o}{V}, \quad \delta = \frac{m}{M}$$

The algebraic manipulations required to obtain (9) from (7) and (3) are substantial but straight forward.

Section VI: Results and Discussion

For purposes of numerical computation we have set

$$\omega_y = 14.6 \text{ rad/sec}$$

$$v_o = 14.6 \text{ ft/sec.}$$

This amounts to the assumption that the basic or reference vehicle speed is 10 miles per hour and the frequency of vehicle frame on its suspension (tires rigid etc.) is 2.33 cycles per sec.

We have also set

$$\frac{a}{\ell} = 0 \quad (\text{tire foot print length zero})$$

$$\delta = \frac{1}{20} \quad (\text{tire mass } \frac{1}{20} \text{ of frame mass})$$

$$\frac{1}{k}^2 = 3.00$$

$$\epsilon_1 = 1 \quad (\text{tire damping same as suspension damping})$$

$$\epsilon_2 = 1 \quad (\text{tire spring modulus same as suspension spring modulus})$$

The quantities ℓ , α , ζ_y and z/ℓ will be varied in the computations.

The results of the computations are given in Figures 3-8. In each figure, the abscissa is ℓ (in ft.) and the ordinate is the variance σ^2 of $\ddot{Y}(t) + Z \ddot{\Theta}(t)$. The scale of the ordinate axis is only relative, as we are only interested in relative values of σ^2 . In Figures 3-5, $z/\ell = 0$; i.e., the point of interest on the frame is C_o . In Figure 6-8, $z/\ell = 1$; i.e., the point of interest on the frame is $\ell/2$ ft forward of the front wheel. Three vehicle speeds are considered: $\nu = 1$ ($v = 10$ mph), $\nu = 1.2$ ($v = 8.33$ mph), and $\nu = .8$ ($v = 12.5$ mph). The values of ζ_y used are indicated in each Figure.

It is important to realize that the results presented and remarks which follow apply only to a specific vehicle configuration with tires clinging to the track at all times. If the configuration is changed geometrically, or if different assumptions are made concerning the tire behavior, different results may be obtained. Also, the variance of $\ddot{Y}(t) + z \ddot{\Theta}(t)$ is being used as a measure of the roughness of the ride;

the longer the variance the rougher the ride. Different measures of ride roughness may change the results. A later Report will deal with the significance of this measure of ride roughness. Our point is that the results given must be viewed in connection with the vehicle model and ride roughness measure.

A number of observations follow from inspection of Figures 3-8.

First, the ride at the c.g. C_0 of the frame is better than the one forward of the front wheel; the speed and ζ_y being the same. Thus, the contribution of frame pitch to our ride roughness is substantial.

Second, an increase in speed from 8.33 mph ($\nu = 1.2$) to 12.5 mph ($\nu = .8$) produces a substantial increase in the roughness of the ride. This points to the fact that the slope of the p.s.d. curve $p_{y0}(\lambda)$ in the range $0 < \lambda < .06$ may be an important parameter in defining ground roughness. For, if the p.s.d. curve had a small slope or were flat in this region, the ride roughness would change but little with these speed changes.

Third, there is no change in ride roughness (with the same ζ_y and ν) with change in l when l is larger than approximately 14 feet. Thus, ride cannot be improved by a change in wheel base length if $l > 14$ ft.

Fourth, substantial changes in ride roughness occur (with the same ζ_y and ν) with changes in l when l is between 4 ft. and 14 ft. In particular, there is a length for best ride and for worst ride. The worst ride at C_0 occurs when l equals approximately 8 ft. The length for best ride is too short to be of practical significance.

Fifth, damping is a significant parameter in determining the roughness of a ride. However, differences due to damping are not as substantial as those due to length change. Thus, artificial means of effectively changing length merit consideration.

Additional computations indicate that drastic changes in the slope of the "tails" portion of the curves do not significantly influence the results in Figures 3-8. Thus, the slope of the $p_{y0}(\lambda)$ curve in the range $\lambda > 0.06$ is not important for the vehicle considered. The possibility therefore exists that the two-foot spacing used in ground surveys may be lengthened to 4 ft., since such survey data still define the p.s.d. curve in the range $\lambda < 0.125$.

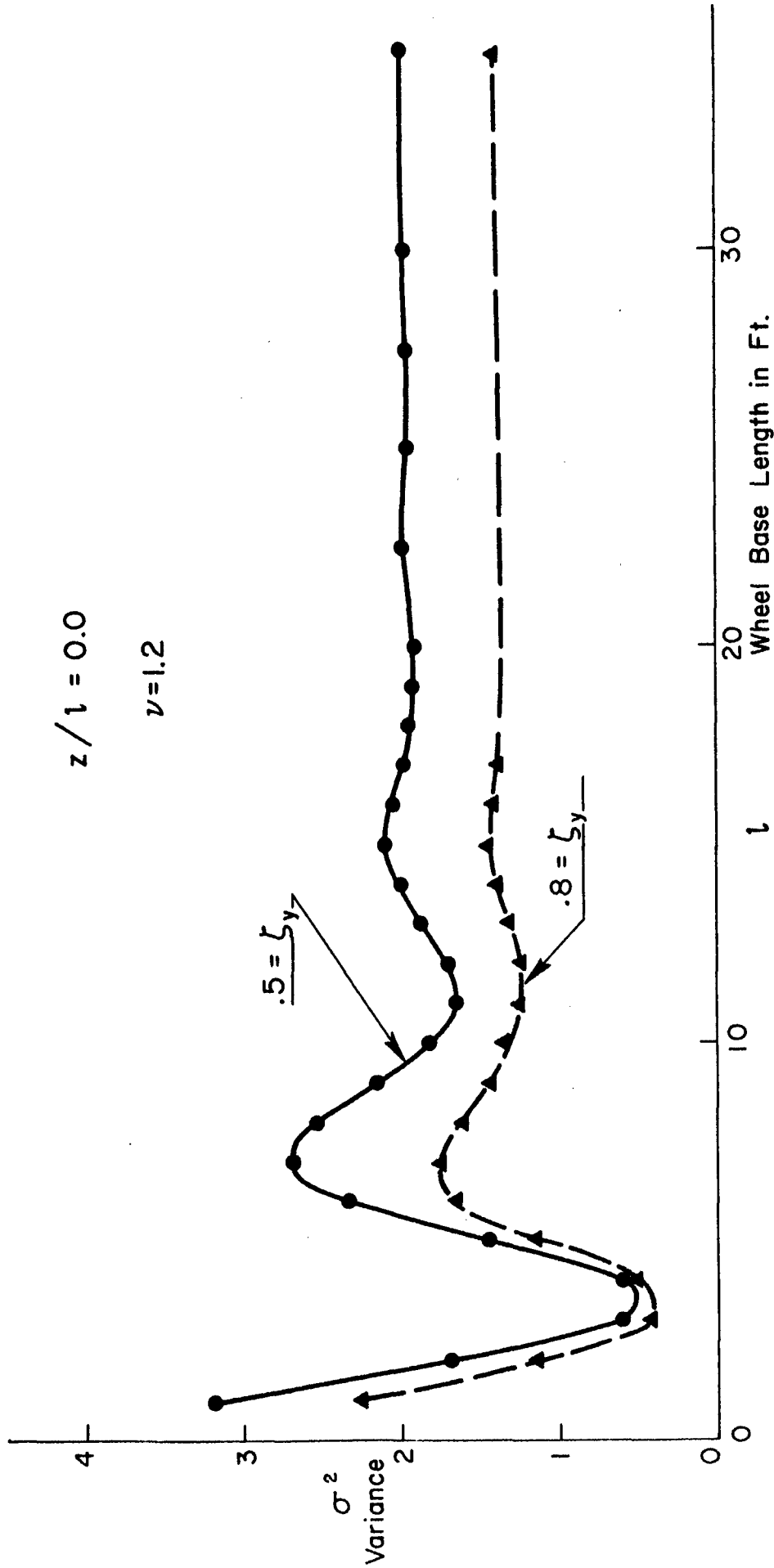


Figure 3.

Variance of Vertical Acceleration of Ride as Function of Wheel Base Length. Location, Speed, and Damping as Indicated.

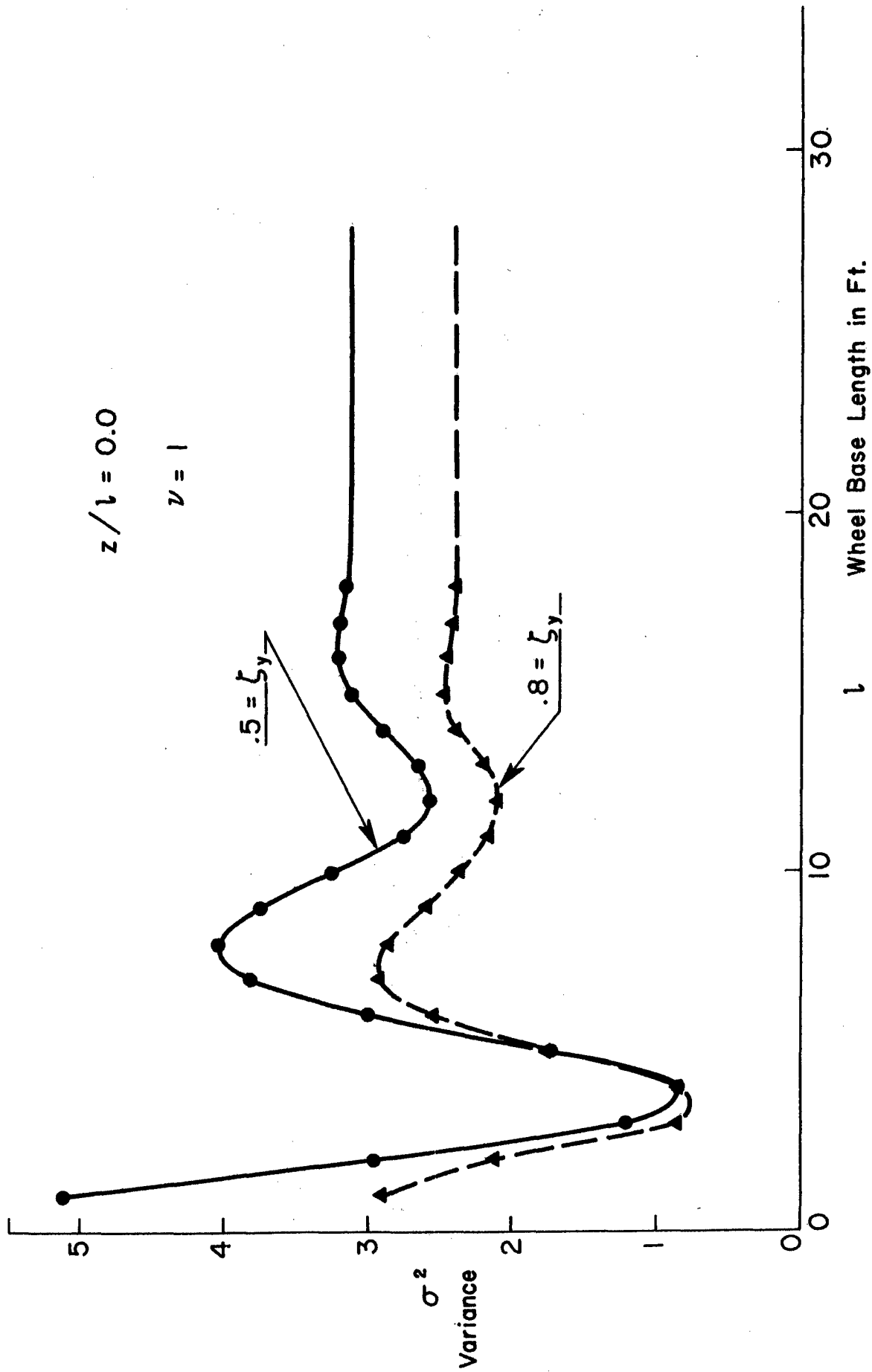


Figure 4.

Variance of Vertical Acceleration of Ride as Function of Wheel Base Length. Location, Speed, and Damping as Indicated.

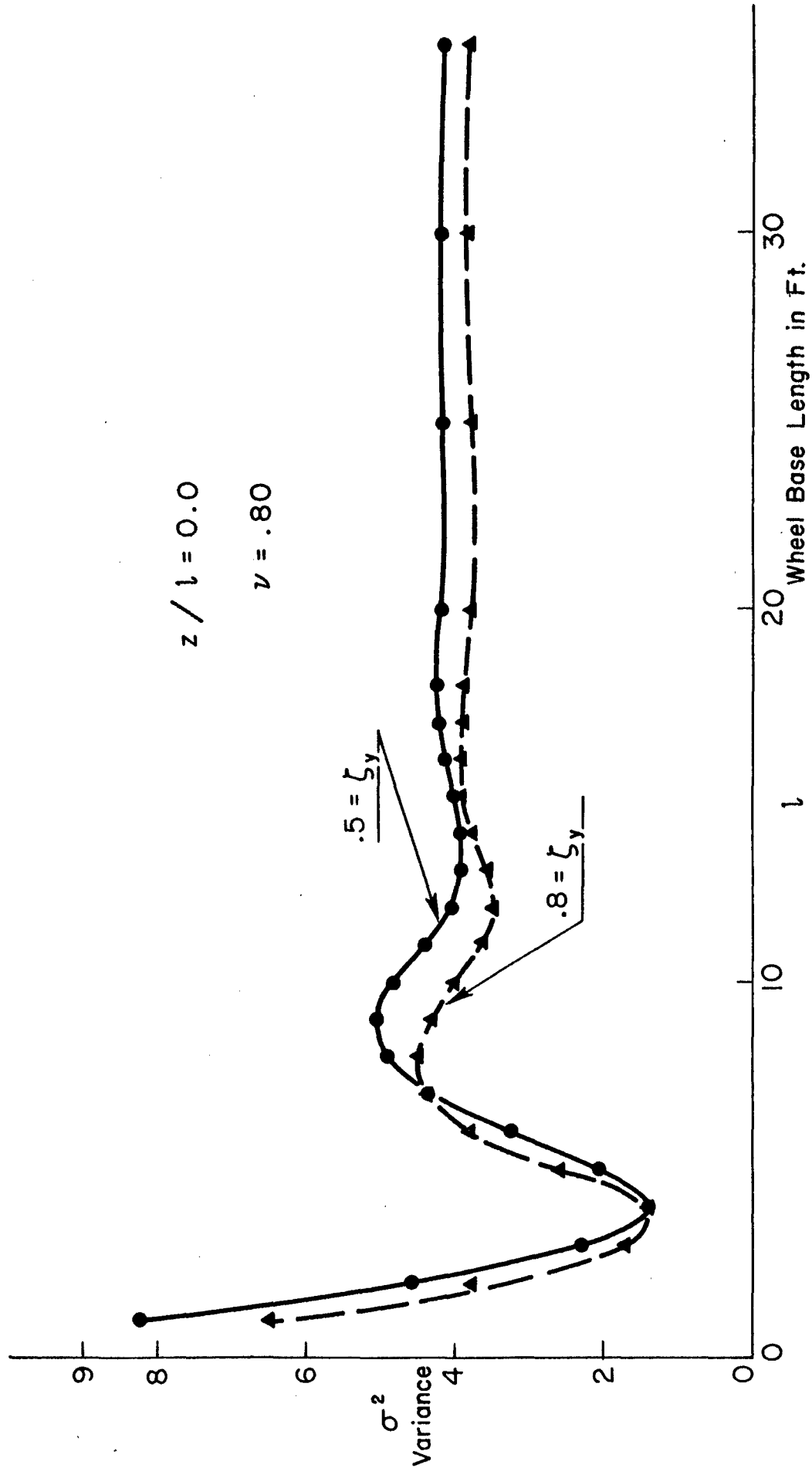


Figure 5.

Variance of Vertical Acceleration of Ride as Function of Wheel Base Length. Location, Speed, and Damping as Indicated.

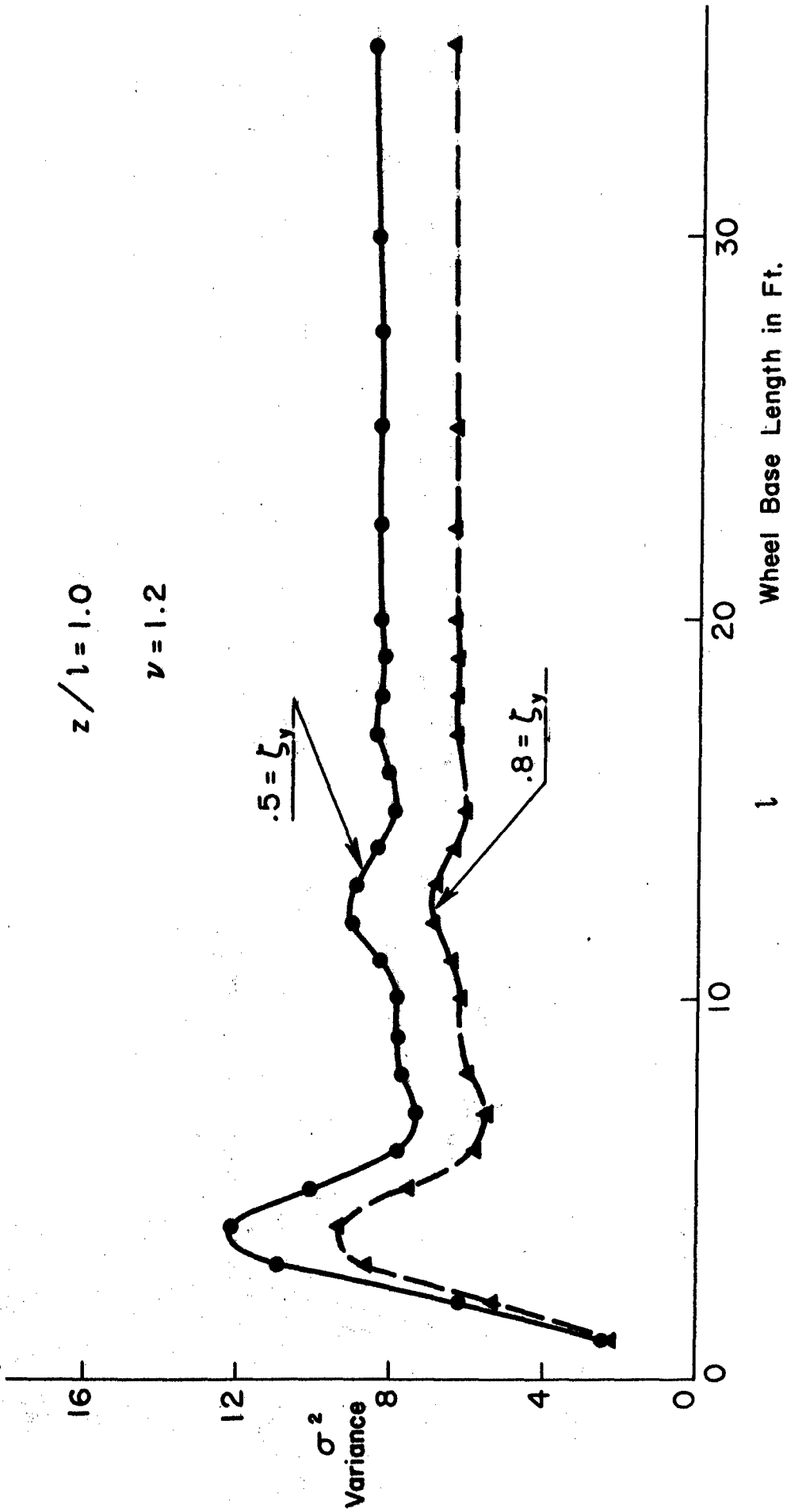


Figure 6.
Variance of Vertical Acceleration of Ride as Function of Wheel Base Length. Location, Speed and Damping as Indicated.

Figure 7.
Variance of Vertical Acceleration of Ride as Function
of Wheel Base Length. Location, Speed, and Damping as Indicated.

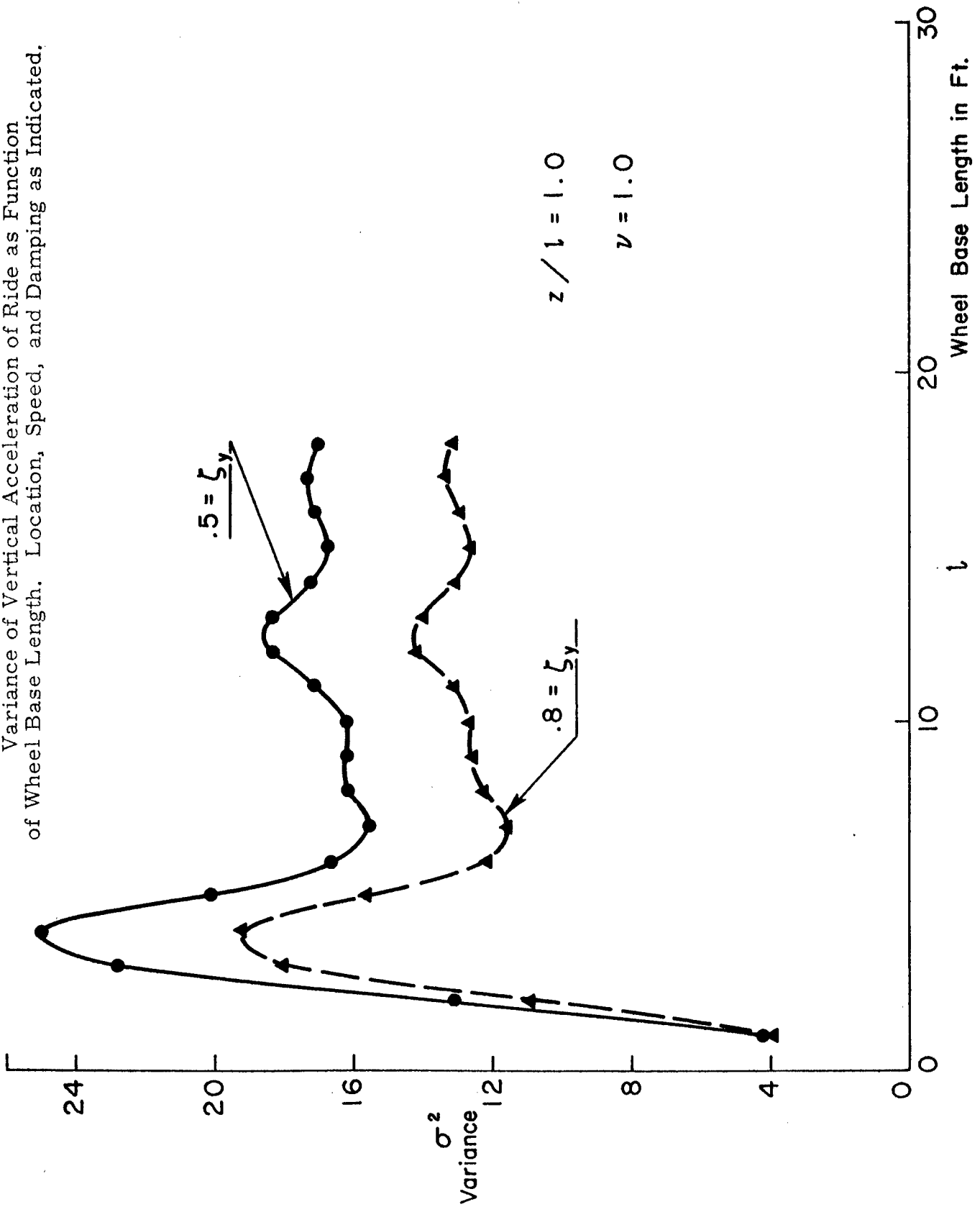
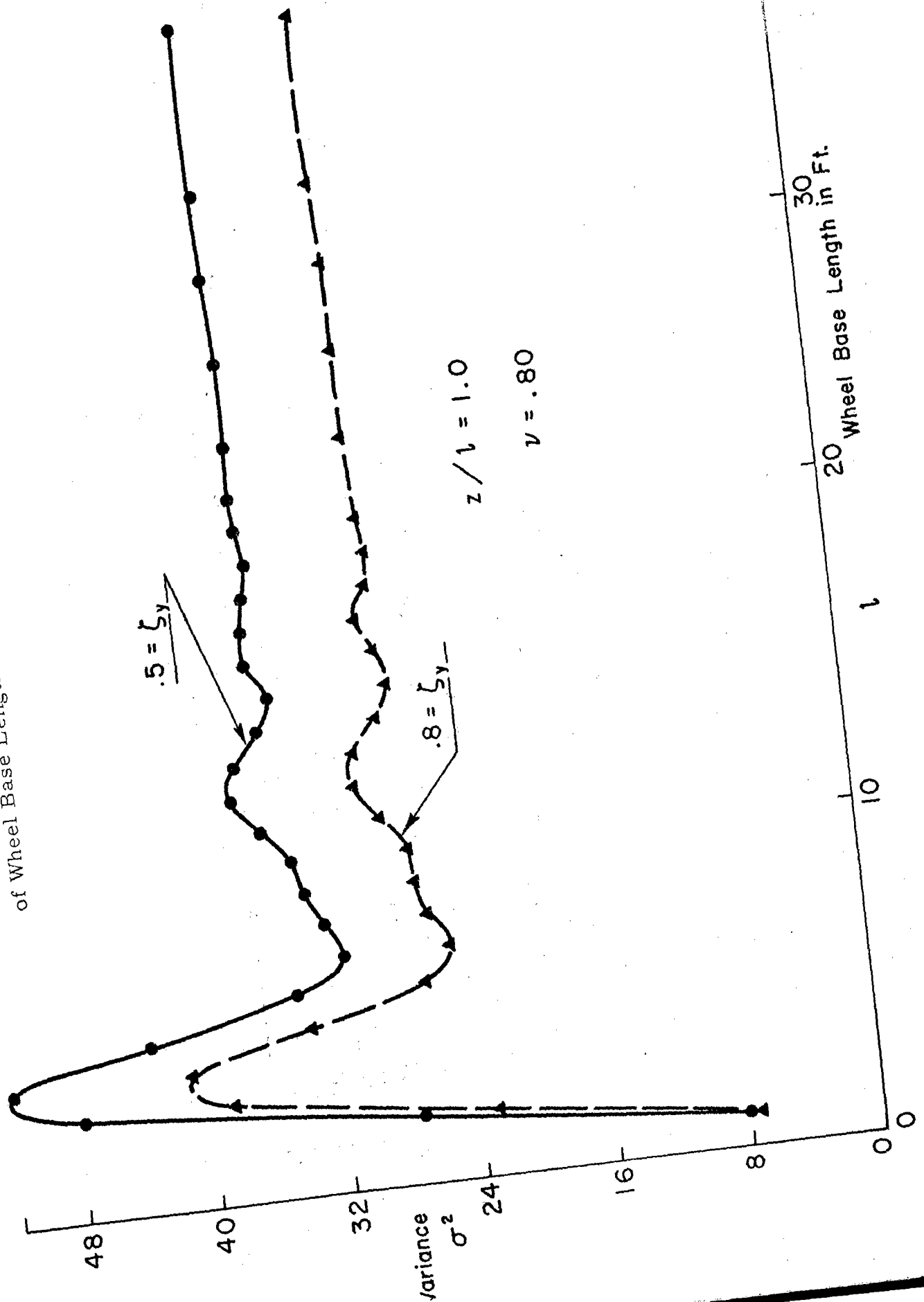


Figure 8.
Variance of Vertical Acceleration of Ride as Function
of Wheel Base Length. Location, Speed, and Damping as Indicated.



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LINEAR VEHICLE USING MEASURED GROUND POWER SPECTRAL
DENSITY by John L. Bogdanoff - Frank Kozin
Report No. 8392 (Final), November 1963, 29 pp., 8 figures
Unclassified Report

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An extension is presented of previous results of the authors relating the parameters of an idealized two-dimensional linear vehicle to stable ground roughness as described by power spectral densities. Optimal vehicle parameters are obtained relative to a ride roughness criterion for ground contours described by power spectral densities estimated from real ground survey data. It is found that the ride is not sensitive to changes in the wheel base length parameter when this is over 14 feet. However, the ride is found to be sensitive to damping and speed in this wheel base length range.

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